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LUMINARY MEMO #203

TO: Distribution
FROM: C. Work, P. Weissman
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SUBJECT: Guidance and Control Stability Tests of LUMINARY 1E

Introduction: motivation behind the tests

In order to avoid the loss of automatic PGNCS attitude control in the event of a switch or bit failure that causes a false AGS indication, PCR 1134 provided that the DAP should (attempt to) control attitude and FINDCDUW should send steering commands even when an AGS indication is present.

The thrust-direction filter in FINDCDUW maintains its estimate of the thrust vector in one of two coordinate frames, depending on the circumstances. If the attitude is not being controlled automatically, a coordinate frame is constructed that is based on the actual current vehicle attitude; in other words, it is based on a reading of the CDUs. However, if the attitude is being controlled automatically, the actual attitude is not used because of the danger that doing so would provide a path for attitude oscillations such as slosh to feed into the steering, which in turn controls the attitude. A steering-slosh interaction could result which could, conceivably, be unstable. This is particularly threatening because the guidance and the slosh have approximately the same period. Furthermore, at the time FINDCDUW was designed, there was considerable uncertainty about the slosh parameters. This closed loop is avoided by not using the actual attitude to construct the coordinate frame for the thrust-direction filter when the steering is automatically controlling the attitude. Instead, the desired attitude, or CDUD vector, is used.

When PCR 1134 was written, it was decided to continue having FINDCDUW use the CDUs when AGS is indicated so that the steering displays would be valid if AGS really were being flown by the astronauts and they were allowing the actual attitude to differ substantially from the desired attitude. As a result, there is

now a possibility of using the actual CDUs for the thrust-direction filter at the same time that the attitude is being controlled automatically. This combination would occur if the LGC received an AGS indication when the primary system actually had control of the attitude. Hence, in this mode, there is a susceptibility to instability that did not exist prior to PCR 1134.

It should be noted that the gain of the thrust-direction filter is rather low, (0.2 in the LM-alone case; 0.1 when docked). This mitigates against any instability being propagated through it. Never the less, it was decided that a program change which bypassed an existing safeguard required investigation. Furthermore, to our knowledge, no explicit study has ever before been made of the guidance-control-slosh interaction over the major LM mission phases with the nominal control configuration (i.e., in PGNCS Auto mode).

Test Plan

An analytical investigation of the transient behavior of this system would have been extremely difficult to carry out with satisfactory rigor because of the important nonlinearities and time-varying components that exist throughout it. For example, the deadband of the RCS control law and the threshold in the angular rate and acceleration estimator are both difficult to include in an analysis. It was decided, therefore, to run a series of simulations on the all-digital simulator in which the response to step changes in attitude and in slosh amplitude could be observed. The magnitudes of the steps were chosen to be somewhat large compared to what could reasonably be expected in actual operation. The assumption is made that the response to any smaller step would be no more severe. Despite the non-linearity of the system, this appears to be a reasonable assumption - particularly since the attitude error and the slosh sweep through smaller values in the time following the step inputs.

The steps in attitude were introduced as ten degree increments to the desired attitude. They were applied to one axis at a time and were cycled through the axes. A step was applied each twenty seconds throughout the powered flight mission phase. The autopilot was given sufficient time (three seconds) to reach the new attitude before the steering was allowed to respond.

The steps in slosh were introduced as forward (+z) displacements of the slosh mass in all tanks simultaneously by a distance equal to 40% of the tank radius. These steps were applied at times that appear to be the most critical.

All tests were made with a PGNCS indication (use CDUDs in the thrust-direction filter) and an AGS indication (use CDUs).

Descent and ascent testing has been completed. A moderate amount of P40 testing is planned but has not yet been carried out.

Descent Results

Attitude Response

AGS indication: RCS during P63 generally added a small increment to the slosh energy after each attitude tweak, but added a larger increment after the tweak at TIG + 420 sec., about 50 seconds before P63 throttle down, when the DPS fuel loading was at about 1/3. During P64, RCS added energy at each tweak, then removed most of the input before the next tweak, with damping following each tweak. The guidance response to the attitude tweaks as measured in terms of desired rate was in the range of 4 to 6 deg/sec in all three axes, increasing toward the high end as the ends of P63 and P64 were approached. The oscillations in guidance desired rates were normal in pattern and were only slightly larger than those for a nominal descent. The desired rate plots never showed the guidance responding to the slosh.

PGNCS indication: Performance was similar to the AGS indicated case except that the RCS input of slosh energy about TIG + 420 sec was more gradual in the PGNCS case.

Slosh Response

AGS indication: Tweaks were applied 60 sec before the P63 throttle-down, 60 sec before P64, 65 sec before P66, and 50 sec before Touch Down. The first tweak was the only one which showed a large DAP response, requiring about 60 seconds to damp out. The others damped more quickly with much less rate

oscillation.

PGNCS indication: Performance essentially duplicated the AGS case results.

Ascent Results

Attitude Response

AGS indication: Generally speaking, the APS removed slosh energy while the RCS added slosh energy, the overall result being a manageable increase in the slosh energy throughout the ascent period. The slosh mass displacements from the tank centerlines showed a series of maxima increasing to .31 tank radii at burn termination, first in the Y axis, then in Z. The RCS fuel consumption was 84.5 lbm, which compares well with a nominal ascent consumption of about 62 lbm, the difference being largely attributable to RCS firings to achieve and then reverse the attitude tweaks. The transient rate response to the attitude tweaks was generally about 6-7 deg/sec, but when a tweak combined with the normal ascent pitch-forward maneuver, the transient rate was -17 deg/sec in the Q axis. V16 N85 was (-0.2, -0.6, +2.9) before trimming.

PGNCS indication: The overall slosh energy build-up was larger than in the AGC case, but still manageable. The slosh mass displacements from the tank centerlines showed a series of maxima increasing to .45 tank radii in the fuel tank and to .37 tank radii in the oxidizer tank at burn termination. RCS fuel consumed was 80.5 lbm. The tweak transient rates were less than 8 deg/sec and the pitch-forward transient rate was -18 deg/sec. V 16 N 85 was (-0.2, +0.2, +2.6) after engine-off and before trimming.

Slosh Response

AGS indication: Tweaks were applied at TIG + 51 sec, at the mid-point of the burn period, and 60 seconds before engine shut-down. The first two tweaks were damped by the APS-RCS combination, but in the thrid case the desired rate oscillations rose to $\pm$ 0.5 deg/sec by engine cut-off, and slosh mass

displacements increased in that period. These guidance-requested oscillations were also present in the PGNS indicated runs, and further work on this problem is reported there. The terminal conditions following this final tweak and ENGINOFF were: N 85 (-0.2, +0.3, +0.9), before trimming.

PGNCS indication: The system responses to the slosh tweaks closely matched the AGS case. The resonant response to the tweak at ENGINOFF - 60 sec was present, whether the CDU frame or the CDUD frame was being used by FINDCDUW. As a result, two more slosh tweak runs were executed, one at ENGINOFF -125 sec and another at ENGINOFF -190 sec. These two tests damped normally with no sign of oscillation in the guidance requested rates. The tweak at ENGINOFF -60 sec resulted in N 85 (0, 0, 0).

Summary

LUMINARY 1E operates successfully in ascent and in descent with an erroneous AGS indication. A resonant oscillation in the guidance-requested rates appeared (both with and without the erroneous AGS indication) after a slosh tweak 60 seconds before engine cut-off, when the APS fuel loading was down to 7%. The resulting attitude oscillations were well within manageable bounds at ENGINOFF, while no oscillatory response from the guidance appeared after earlier slosh tweaks. The descent runs all showed no guidance oscillations in response to attitude tweaks or to slosh tweaks, although there was a small, well-damped overshoot in the guidance-requested rates after each Q or R axis attitude tweak in the descent tests. In all cases, the burn was executed satisfactorily with or without a false AGS indication and in the presence of extreme slosh and attitude transients.